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IMPLICATIONS OF ENERGY EFFICIENCY IMPROVEMENT FOR CO_2 EMISSIONS IN ENERGY-INTENSIVE INDUSTRY

Doctoral Dissertation

Sari Siitonen

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Doctoral dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Faculty of Engineering and Architecture for public examination and debate in Auditorium K216 at the Aalto University School of Science and Technology (Espoo, Finland) on the 27th of November 2010 at 12 noon.

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School of Science and Technology
Faculty of Engineering and Architecture
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Abstract

This thesis explores how energy efficiency improvement implemented in industrial plants contributes towards achieving CO_2 emission reduction. The measurement of energy efficiency and CO_2 emissions are related issues. The implications of the following challenges in measuring energy efficiency have been evaluated based on constructive case studies: variables affecting energy efficiency, the allocation problem, system boundary definitions and energy valuation. In addition, the realisation of emission reduction potential is analysed.

The thesis shows that, among other things, the utilisation of recycled materials is an important variable that has to be taken into account when the energy efficiencies of different plants are compared. In the case of CHP production, some cost allocation methods, such as the energy method, may overestimate the feasibility of heat conservation investment from the industrial mill perspective. Due to heat conservation, CHP electricity production may be reduced at the mill site, which increases the demand for external electricity. The purchase of external electricity has implications for energy consumption and CO_2 emissions at the national level. Therefore, the realised CO_2 reduction of heat conservation investment may seem totally different from the mill site and national perspectives, which demonstrates the importance of the system boundary definition when evaluating the contribution of an individual energy efficiency investment towards fulfilling the commitment to reduce CO_2 emissions. Also, increased operational flexibility and changing market conditions, such as energy and emission allowance prices, complicate the evaluation of the emission reduction potential and often reduce the exploitation of the full emission reduction potential. The thesis contributes to the research on monitoring energy efficiency and CO_2 emissions in connection with the implementation of energy and climate policy.

Keywords Energy efficiency, CO_2 emissions, combined heat and power (CHP) production

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Tekijä Sari Siitonen

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Energiatehokkuuden parantamisen vaikutukset CO_2-päästöihin energiaintensiivisessä teollisuudessa

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Tutkimusala	Teollisuuden energiatekniikka
Vastaväittäjä(t)	Ph.D. Thomas Browne ja Professori Erik Dahlquist
Työn valvoja	Pekka Ahtila
Työn ohjaaja	Mari Tuomaala

Tiivistelmä

Tässä työssä tutkitaan, kuinka energiatehokkuuden parantaminen teollisuuslaitoksissa vaikuttaa CO_2-päästövähennysten saavuttamiseen. Kysymys liittyy läheisesti energiatehokkuuden ja CO_2-päästöjen mittaamiseen. Konstruktiivisten case-tarkastelujen avulla on arvioitu seuraavien energiatehokkuuden mittaamisen haasteiden merkitystä: energiatehokkuuteen vaikuttavat tekijät, allokointiongelma, taserajan määrittäminen ja energian arvottaminen. Lisäksi on arvioitu päästövähennyspotentiaalin realisoitumista.

Tämä tutkimus osoittaa, että muun muassa kierrätysmateriaalien hyödyntäminen on tärkeää ottaa huomioon, kun eri laitosten energiatehokkuuksia verrataan toisiinsa. Yhdistetyn sähkön ja lämmön tuotannon (CHP) tapauksessa eräät kustannusten allokointimenetelmät, kuten energiamenetelmä ja hyödynjakomenetelmä, saattavat yliarvioida lämmönsäästöinvestoinnin kannattavuutta tehtaan näkökulmasta. Lämmönsäästö voi vähentää CHP-sähkön tuotantoa tehdasalueella, mikä lisää ostosähkön tarvetta. Sähkön osto vaikuttaa energiankulutukseen ja CO_2-päästöihin kansallisella tasolla. Näin ollen lämmönsäästöinvestoinnin ansiosta saavutettavat CO_2-päästövähennykset saattavat näyttää tehdastasolla aivan erilaisilta kuin kansallisella tasolla, mikä osoittaa taserajan määrittämisen tärkeyden, kun arvioidaan yksittäisen energiatehokkuusinvestoinnin merkitystä päästövähennystavoitteen saavuttamisessa. Lisäksi toiminnan joustavuuden lisääminen ja muuttuvat markkinaolosuhteet, kuten energian ja päästöoikeuden hinnat, vaikeuttavat päästövähennyspotentiaalin arviointia ja usein myös saavutetut päästövähennykset jäävät alhaisemmiksi kuin saavutettavissa oleva maksimipotentiaali. Tämä työ edistää tutkimusta, joka liittyy energiatehokkuuden ja CO_2-päästöjen tarkkailuun osana energia- ja ilmastopolitiikan toteuttamista.

Asiasanat Energiatehokkuus, CO_2-päästöt, yhdistetty sähkön ja lämmön tuotanto (CHP)

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One day my six-year-old daughter, Netta, wanted to play with me and asked:
"Mama, why do you have to do that stupid Ph.D.?"
I answered: "I don't know."
Of course, it was a quick and easy answer
that I use far too often.

Later on I wondered why,
and I realised that actually the question "why" motivates thinking.

A child tries to understand the world by asking "why".
The adult's way to find a better understanding of the world
is to do a "stupid" Ph.D.

To my daughters, Lotta and Netta.

Preface

This study has been conducted in the Department of Energy Technology at the Aalto University School of Science and Technology. My instructor was Dr. Mari Tuomaala and the study was supervised by Professor Pekka Ahtila.

First, I would like to thank Mari for numerous pieces of good advice and for reminding me over and over again about the importance of bearing in mind the thread running through the thesis. I am most grateful to Pekka, who once again managed to talk me into the research project. Also, the other co-authors of research papers, Dr Henrik Holmberg and Markku Suominen, are greatly acknowledged.

I wish to thank the whole research team of Industrial Energy Engineering for interesting lunchtime discussions and for trying to push me towards jogging exercises. I thank my room-mate, Suvi, for creating such a positive working atmosphere. I am especially thankful to Helena for managing all the practical things and for organising pleasant summer trips and other events outside the office.

This study has been financed by the Finnish Funding Agency for Technology and Innovation (Tekes) under the ClimBus programme. In addition, Rautaruukki Foundation has supported me during the study. I am grateful to my employer, Gasum, especially my boss Christer Paltschik, for understanding the time requirements of the research work. The personnel of the case mills of this study are greatly acknowledged for providing the energy consumption data used in this research. I would like to thank Richard Walker for checking the English language of the articles I-V and the Summary.

I am grateful to all my friends for being there for me whenever I needed support and encouragement. I want to thank “The Seiskat” for offering a fruitful “breeding ground” for my motivation to do research work and for thinking in general.

I thank my Mother and Ulla and Katja for their support and for instilling in me the importance of having the right attitude. I am grateful to Tarja and Joke for helping in childcare and many other things. I thank Touho for his patience and love. Finally, thanks go to my darlings, Lotta and Netta, for showing me - every day - what really matters.

Contents

List of Publications

This thesis consists of an overview and the following publications, which are referred to in the text by their Roman numerals.

I Siitonen, S., Tuomaala, M., Ahtila, P., Variables affecting energy efficiency and CO_2 emissions in the steel industry, Energy Policy, 38 (2010), 2477-2485.

II Siitonen, S., Tuomaala, M., Ahtila, P., Influences of material recycling on energy efficiency, Case: iron and steel industry & pulp and paper industry, Proceedings of International Conference of Applied Energy 2010, Singapore, 794-805.

III Siitonen, S., Holmberg, H., Estimating the value of energy saving in industry by different cost allocation methods, International Journal of Energy Research (2010). Accepted for publication.

IV Siitonen, S., Tuomaala, M., Suominen, M., Ahtila, P., Implications of process energy efficiency improvements for primary energy consumption and CO_2 emissions at the national level, Applied Energy, 87 (2010), 2928-2937.

V Siitonen S., Ahtila P., The influence of operational flexibility on the exploitation of CO_2 reduction potential in industrial energy production, Journal of Cleaner Production 18 (2010), pp. 867-874.

Author's contribution

Papers I, II, IV and V are independent research carried out and written by the author. The author initiated Paper III and was mainly responsible for its writing. The co-author, Dr Henrik Holmberg, made the calculations related to the market-based method and wrote the description of that methodology. Dr Mari Tuomaala contributed to the structure of papers I, IV and V. Senior Advisor Markku Suominen from Pöyry Finland Oy commented on paper IV, and Professor Pekka Ahtila commented on papers I, II, IV and V.

List of Abbreviations

ADEME	The French Agency for the Environment and Energy Management
APEC	Asia Pacific Energy Research Centre
BAT	best available technology
BREF	reference document on best available techniques
CCGT	combined cycle gas turbine
CCS	carbon capture and storage
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
CEPI	Confederation of European Paper Industries
CHP	combined heat and power
CIPEC	Canadian Industry Program for Energy Conservation
CO_2	carbon dioxide
CSPA	Canadian Steel Producers Association
DHC	district heating and cooling
EC	European Commission
EEI	energy efficiency index
EUA	EU allowance
EU ETS	European Union Emissions Trading Scheme
GDP	gross domestic product
HVAC	heating, ventilating and air conditioning
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
JISF	Japan Iron and Steel Federation
LCA	life cycle assessment
MEE	Finnish Ministry of Employment and the Economy
MILP	mixed-integer linear programming
NGL	natural gas liquids
NGO	non-governmental organisation

NRCAN	Natural Resources Canada
OECD	Organization for Economic Cooperation and Development
Paprican	Pulp and Paper Research Institute of Canada
PEC	primary energy consumption
PLS	partial least squares projection to latent structures
SEC	specific energy consumption
Tekes	Finnish Funding Agency for Technology and Innovation
TPES	total primary energy supply
VTT	Technical Research Centre of Finland
UN	United Nations
WEC	World Energy Council
WEO	World Energy Outlook

1 Introduction

Climate change is one of the central energy challenges and it could become the main driver of energy policy in the coming decades (IEA, 2009a). In the Copenhagen Accord (2009), an even stronger statement was made: “Climate change is one of the greatest challenges of our time.” In Copenhagen, the world’s leaders agreed to reduce global emissions so that the increase in global temperature is limited to 2°C compared to pre-industrial levels. However, legally binding emission reduction targets were not agreed.

The European Union is a leader in taking action to mitigate climate change (IEA, 2008a). The European Union has set so-called 20-20-20 targets for (1) reducing its CO_2 emissions by at least 20%, (2) increasing the proportion of renewable energies in its energy mix to 20% and (3) reducing its energy consumption by 20% by 2020. In the Action Plan for Energy Efficiency (EC, 2006a), the target for reducing energy consumption is specified as a 20% saving in annual consumption of primary energy by 2020 compared with the energy consumption forecasts for 2020.

The targets to reduce emissions and increase the share of renewable energy are legally binding targets (EC, 2009a; EC, 2009b), whereas the target to reduce energy consumption is not. The Energy Services Directive (EC, 2006b) is the only document that sets an indicative energy-saving target of 9% between the years 2008 and 2016. However, this target does not apply to the actors involved with the European Union Emissions Trading Scheme (EU ETS), such as the pulp and paper industry and the iron and steel industry.

Renewable energy and energy efficiency improvement are key measures to reduce CO_2 emissions. Actually, the improvement of energy efficiency is regarded as the fastest and cheapest way of reducing CO_2 emissions (IEA, 2007a). Energy efficiency also plays an important role in reducing dependence on energy resources and lowering energy costs (EC, 2009c).

Although energy efficiency has been a high priority of energy regulations and policymakers for decades, it has not fully met the level of emissions reduction expected by experts (Vine & Hamrin, 2008). Neither has improvement in energy efficiency led to energy savings, regardless of the tendency for new plant and appliances to be more efficient than those they replace (Herring, 1999). Instead, some of the savings due to energy efficiency improvement have taken the form of higher consumption of products or a higher level of services. For example, industrial output increased 39% in the 21 IEA[1] countries between 1990 and 2005, and regardless of big improvement in energy efficiency, the final energy use in industry increased 5% (IEA, 2008b). The growth of

[1] 21 IEA countries include: Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Greece, Italy, Japan, Republic of Korea, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom and United States

the production of energy-intensive industrial products is expected to continue with increased population and income per capita (Bernstein et al., 2007).

Since the 1970s there has been a strong correlation between economic growth and primary energy consumption: each 1% increase in global gross domestic product (GDP) was accompanied by a 0.7% increase in primary energy consumption (IEA, 2009a). According to IPCC (Bernstein et al., 2007), industrial sector final energy, primary energy and energy-related CO_2 emissions[2] increased between 1990 and 2004 by 18%, 22% and 18%, respectively.

Among others, Campbell (1996) and Ainoa et al. (2009) have pointed out the conflicts between different aspects of sustainable development, i.e. economic growth, environmental protection and social equity. Hueting (2010) has stated that environmental sustainability cannot be attained with a growing production. Instead, recent evidence suggests that the economic recession triggered by the financial crisis, which started in mid-2007, has led to a drop in energy use, CO_2 emissions and energy investment (IEA, 2009a). Lately, the efforts towards continuous economic growth and overconsumption has been criticised by, among others, the degrowth thinkers (Wikipedia, 2010).

There might be conflicts between energy efficiency and emission reduction, too. Technologies such as wastewater treatment and flue gas cleaning reduce environmental burdens but may complicate processes and increase the internal energy consumption of an industrial plant. For example, tightened environmental requirements have increased the specific electricity consumption in the pulp and paper industry (Siitonen & Ahtila, 2002). Increased primary energy demand leads often also to higher CO_2 emissions. Also some new technologies under development that are expected to contribute towards meeting the CO_2 emissions reduction targets, such as carbon capture and storage (CCS), increase energy consumption: depending on the power plant type, the fuel consumption increases by 10-40% compared to a conventional power plant (Teir et al., 2009).

At the company level the decision-making is typically based on economic optimisation. Therefore, the motivation to protect the environment is often related to economic benefits or obligations dictated by environmental legislation. Since 2005, the CO_2 emission reduction target has been allocated to the industrial operators under the EU ETS and CO_2 emissions have had a monetary value. Therefore, the price of an EU allowance (EUA) is an additional variable taken into account in the economic optimisation. Also, the motivation to improve energy efficiency is often related to cost savings.

As shown above, depending on the case, the targets to reduce CO_2 emissions and reduce energy consumption may be convergent or may compete with each other or some other targets. Although these targets are challenging and the timetable is tight, there is not yet a clear understanding of how energy efficiency improvement contributes towards to meeting emission reduction targets. This question is especially interesting from the

[2] Energy-related CO_2 emissions including indirect emissions from electricity use.

industrial sector point of view, because of highly integrated processes and high energy consumption. In 2005, industry accounted for one third of the global primary energy use and around 25% of global energy and process CO_2 emissions (IEA, 2008c). In Finland, the share of manufacturing industry in final energy use has been as high as 50% (Statistics Finland, 2008).

Therefore, the main research question of this study is:

How does energy efficiency improvement in industrial processes contribute towards achieving CO_2 emissions reduction?

Evaluating the implications of energy efficiency improvement for CO_2 emissions is based on the measurement of energy efficiency, which has been shown to be a complicated task in industry (Tuomaala, 2007). Among others, the following challenges related to the measurement of energy efficiency have been identified: variables affecting energy efficiency, the allocation problem, system boundary definitions and energy valuation (Patterson, 1996; Ahtila et al., 2010).

The realisation of the CO_2 emission reduction potential of individual energy efficiency projects has been monitored under the Kyoto mechanisms. However, the factors affecting the realisation of the emission reduction potential have not really been studied before. Therefore, in this thesis the main research question is considered with two different approaches:

1. The evaluation of different challenges involved in measuring energy efficiency and the related CO_2 emission reduction;

2. The analysis of the realisation of the energy conservation and CO_2 emission reduction potential in energy-intensive industries.

In section 2 the objective and scope of the thesis are presented in greater detail. Section 3 defines the concepts of energy efficiency, energy saving and energy use, and also reviews previous energy efficiency studies found in the literature. Section 4 presents and discusses the results of the individual papers. Finally, conclusions drawn from the key findings are presented in section 5.

2 Objective and scope of the thesis

The objective of this thesis is to contribute to the understanding of the implications of energy efficiency improvement for CO_2 emissions in energy-intensive industries. In this study the focus is on the pulp and paper industry and the iron and steel industry, because they are the major industrial energy consumers in Finland: their shares of the total energy used in all manufacturing were 51% and 15%, respectively (Statistics Finland, 2010a). In 2008 those industries together accounted for around 27% of total energy consumption and around 38% of electricity consumption in Finland (Finnish Energy Industries, 2009a). In 2008, industry was responsible for about 25% (18 Mt CO_2 equivalent) of the total anthropogenic greenhouse gas emissions in Finland. Compared to energy use, the share of CO_2 emissions is low because of the high consumption of renewable carbon-free energy in the forest industry (Statistics Finland, 2010b).

This thesis includes five appendix papers:

I Siitonen, S., Tuomaala, M., Ahtila, P., Variables affecting energy efficiency and CO_2 emissions in the steel industry, Energy Policy, 38 (2010), 2477-2485.

II Siitonen, S., Tuomaala, M., Ahtila, P., Influences of material recycling on energy efficiency, Case: iron and steel industry & pulp and paper industry, Proceedings of International Conference of Applied Energy 2010, Singapore, 794-805.

III Siitonen, S., Holmberg, H., Estimating the value of energy saving in industry by different cost allocation methods, International Journal of Energy Research (2010). Accepted for publication.

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V Siitonen S., Ahtila P., The influence of operational flexibility on the exploitation of CO_2 reduction potential in industrial energy production, Journal of Cleaner Production 18 (2010), pp. 867-874.

Different challenges involved in measuring energy efficiency and the related CO_2 emission reduction have been evaluated as follows:

- Variables affecting energy efficiency and CO_2 emissions are considered in Paper I. Paper II concentrates on only one factor, i.e. material recycling, affecting energy efficiency.

- The allocation problem has been studied in two different papers: in Paper II how to allocate the benefits of material recycling between primary and secondary production and in Paper III how to allocate the fuel consumption of a CHP plant to heat and electricity so that plant level decision-making would support energy efficiency improvement.

- Definition of the system boundary is an essential basic step in all energy studies and therefore this issue is widely considered in papers I, IV and V. Also in Paper III different decision-making perspectives are related to the system boundaries.

- The valuation of energy is discussed in papers III and V. Paper III concentrates on the thermodynamic value of energy in relation to the exergy allocation method and paper V focuses on the monetary value of energy.

The realisation of the energy conservation and CO_2 emission reduction potential in energy-intensive industries is analysed in the following papers:

- Paper IV analyses the effects of system boundary selection on the realisation of primary energy savings and CO_2 emission reduction.

- Paper V studies how operational flexibility and changes in energy prices affect the realisation of the energy conservation and CO_2 reduction potential of an energy efficiency investment.

Paper I focuses on the iron and steel industry and papers III, IV and V on the pulp and paper industry. Both the iron and steel industry and the pulp and paper industry are dealt with in Paper II.

In Paper I specific energy consumption is considered at the mill site and mill levels, whereas national level analysis and international benchmarking are used in Paper II. Papers III-V concentrate on energy production in industry and its integration into the system; the focus is on CHP production because on-site energy production in the Finnish pulp and paper industry is widely based on CHP production.

This study is based on constructive case studies. The following methodologies and source data have been used in the case studies documented in the appendix papers I...V:

- In Paper I, the partial least squares projection to latent structures (PLS) analysis is used to analyse the correlations between the selected variables. Process data from the iron-ore-based steelmaking process were used as the basis of that analysis.

- Paper II is based on statistical analysis where various international statistics were used for collecting the input data.

- In Papers III-V process data from pulp and paper mills were used as input data in the process modelling of industrial power plant processes. In addition, the energy analysis reports, including real energy conservation data from five Finnish pulp and paper mills, were used as a source material in Paper IV. The process modelling was made by Solvo®, which is a commercial software application developed by Fortum for modelling and simulating the heat balances of a power plants.

3 Literature review: energy efficiency and CO_2 in industry

In this chapter the definitions of energy efficiency and energy use are presented. Then, the energy efficiency and CO_2 indicators used in industry are described and the results of relevant earlier studies reviewed.

3.1 Definitions of energy efficiency and energy saving

The terms ‘energy efficiency’, ‘efficient use of energy’ and ‘energy conservation’ are in many contexts seen as synonyms or partly overlapping concepts (VTT, 2007). However, there are differences between these terms:

- Energy efficiency is defined by the Energy Services Directive (EC, 2006b) as “*a ratio between an output of performance, service, goods or energy, and an input of energy*”.

- Efficient use of energy is defined by VTT (2007) as “*the minimum possible energy used to produce some specified useful output through a process, product or service*”.

- Energy conservation (also called energy saving) is defined by VTT (2007) as *“a decrease in energy consumption in absolute terms over some period of time”*.

Energy efficiency improvement can either mean that 1) an unchanged output is obtained with lower energy input, 2) an increased output is obtained with an unchanged energy input or 3) the relative increase in output is greater than that of energy input (EC, 2009c). Actually, 1) and 2) are special cases of 3). However, there might be different variables behind energy efficiency improvement if the output changes instead of the energy input.

Energy conservation can be achieved by improving the energy efficiency or by reducing the amount or quality of the produced services (VTT, 2007).

The definition presented above for efficient use of energy represents the ideal case where there are no losses in the process. However, in the real world there are losses in all processes, and this applies also to the potential for energy conservation. Tuomaala (2007) and VTT (2007) divided energy conservation potentials into theoretical, technical and economic potentials. Theoretical potential represents the maximum improvement opportunities available. Technical and economic potentials consider technological restrictions and economic constraints, respectively. In addition, Tuomaala (2007) stated that the potential for improvement is greatest in the process design phase. In the operational phase, when the structure of the process and its connections to the external environment have already been determined, the efficiency can be improved mainly through adopting better operational practices (Tuomaala, 2007). Retrofitting an existing facility of an existing system can provide bigger improvements, but often it is a more expensive alternative. A new facility would show even greater improvements with higher capital costs. However, the operational costs are often lower, so sometimes the replacement of an old facility is a reasonable option.

Despite the existence of significant potential for cost-effective investment in energy efficiency, market barriers and market failures prevent its exploitation (IEA, 2007b; Brown, 2001). Brown (2001) named this difference between the cost-efficient investments in energy efficiency and the actual level of investment as the ‘‘efficiency gap’’. VTT (2009) uses the term “expected energy efficiency potential” for the potential where the effects of barriers and obstacles have been taken into account. The IEA (2007b) lists the following market barriers: low priority of energy issues, lack of access to capital, and the incomplete market for energy efficiency. Market failures occur when markets do not operate efficiently. Examples of market failures are split incentives, i.e. different goals or incentives of participants in an economic exchange, and insufficient and inaccurate information. Also low energy prices may weaken the profitability of energy efficiency improvement and prevent investments.

Realisation of emission reduction potential requires different policy measures in different cases, such as regulation, economic control, sustainable planning, guidance or their combination (Vehviläinen et al., 2008). Energy savings certificates, also called white certificates, can be used in reducing greenhouse gas emissions (Vine & Hamrin, 2008). In addition, standardisation provides tools to follow legislation (EC, 2010). The European standardisation organisations CEN and CENELEC published a new standard EN 16001 on energy management in July, 2009. In addition, there are many standards under development including EN 15900 on energy efficiency services and standards on benchmarking methodologies for energy uses and energy audits (Gindroz, 2009).

3.2 Definitions of energy use

Energy use can be measured as ‘primary energy use’ and ‘final energy use’ (IEA, 2008c). Also the terms ‘primary energy consumption’ or ‘final energy consumption’ are used. The use of terms such as ‘energy production’ or ‘energy consumption’ is sometimes criticised because the first law of thermodynamics states that energy cannot be created or destroyed, only transformed from one form to another. However, these terms are widely used and they can basically be understood to mean the transformation of energy (EC, 2009c).

The Organization for Economic Cooperation and Development (OECD, 2010) defines primary energy consumption as ‘*the direct use at the source, or supply to users without transformation, of crude energy, that is, energy that has not been subjected to any conversion or transformation process*’ The source publication for this definition is the United Nations’ Glossary of Environment Statistics (UN, 1997). According to IEA (2009b) primary energy includes hard coal, lignite/brown coal, peat, crude oil, natural gas liquids (NGL), natural gas, combustible renewables and waste, nuclear, hydro, geothermal, solar and the heat from heat pumps that is extracted from the ambient environment. Usually the term 'total primary energy supply (TPES)' is used. In this thesis primary energy consumption has been interpreted to include the energy consumption of the plant in question but not the energy consumption during the previous stages of the fuel cycle, such as fuel production, transportation or storage.

Primary energies are converted to secondary energies, such as electricity, steam or oil products, in transformation processes. From the energy consumer point of view, for example the waste heat from the industrial processes can also be called secondary energy.

Final energy can be either primary (e.g. natural gas) or secondary (e.g. electricity) energy (EC, 2009c). IEA (2008b) defines final energy as '*the energy supplied to the consumer in each end-use sector, which is ultimately converted into heat, light, motion and other energy services*'. However different definitions and terms are used in different statistics.

Eurostat (2009) uses the term 'gross inland consumption' instead of primary energy consumption and divides final consumption into 'final non-energy consumption' and 'final energy consumption'. Non-energy consumption includes mainly energy used for oil refining in the chemical industry.

In Finnish energy statistics the terms 'total consumption of energy' and 'final consumption of energy' are used. Total consumption of energy describes fuels used in the production and processing of energy, and energy used in direct, final consumption. Total consumption of energy includes data on the use of fossil fuels, energy peat, renewable energy sources, nuclear energy and net imports of electricity. Final consumption of energy measures the consumption of final energy products, i.e. electricity and heat and fuels used for space heating of buildings, transport and industrial processes. (Statistics Finland, 2010c)

The organisations supervising the interests of different industries, such as Confederation of European Paper Industries (CEPI), have their own ways to collect and present statistics. CEPI (2009) presents total primary energy consumption, including the fraction of biomass in total primary energy consumption. In addition, total electricity consumption – divided into total electricity produced at the site, purchased electricity and sold electricity – is presented.

Regardless of the different terms used in different statistics, basically they all consider both primary and final energy consumption. Final energy consumption differs from primary energy consumption or total energy consumption in that it does not include energy transformation / conversion and transmission / distribution losses. In this thesis the terms 'primary energy consumption (PEC)' and 'final energy consumption' are used.

3.3 Energy efficiency and CO_2 indicators

There are a number of indicators which can be used to monitor changes in energy efficiency (Patterson, 1996). In industry, specific energy consumption (SEC) is the most commonly used measure of energy efficiency. Sometimes, the terms ‘energy intensity’ (IEA, 2007c, NRCAN/CSPA, 2007), ’energy intensity value’ (Worrell et al., 2008) or ‘energy consumption intensity’ (Tanaka, 2008) are used instead of SEC.

SEC is a physical-thermodynamic indicator defined as (EC, 2009c)

$$SEC = \frac{energy\ used}{products\ \ produced} = \frac{energy\ imported - energy\ exported}{products\ \ produced} \tag{1}$$

where SEC is measured in GJ/t, i.e. the indicator reflects the ratio of energy input and output as physical products. SEC can be used to analyse trends in energy efficiency in a manufacturing process, sector or even at the national level.

Industrial processes often use energy in different forms, such as fuels, steam and electricity, and the SEC of such processes is calculated as (EC, 2009c)

$$SEC = \frac{E_{Fuels} + E_{Steam} + E_{Electricity}}{products\ \ produced} \tag{2}$$

where E_{Fuels} is fuel consumption, E_{Steam} is steam consumption and $E_{Electricy}$ is the electricity consumption of the process. Eq. (2) defines SEC as final energy consumption. If the energy consumption of steam and electricity production is taken into account, the SEC as primary energy consumption is defined as (modified based on EC, 2009c)

$$SEC_{Primary} = \frac{E_{Fuels} + \dfrac{E_{Steam}}{\eta_{Steam}} + \dfrac{E_{Electricity}}{\eta_{Electricity}}}{products\ \ produced} \tag{3}$$

where η_{Steam} is the efficiency of steam production and $\eta_{Electricity}$ is the efficiency of electricity production.

In order to monitor the progress of energy efficiency, an energy efficiency index (EEI) is defined as

$$EEI = \frac{SEC_{ref}}{SEC} \tag{4}$$

where SEC_{ref} is the reference value for the specific energy consumption. The reference value can be defined on the basis of the best available technology (BAT), a benchmark value of the product in question, or a specified reference period.

Similarly, the specific CO_2 emissions, also called CO_2 intensity (IEA, 2007c) or CO_2 emission-intensity indicator (NRCAN/CSPA, 2007), of industrial products can be calculated as

$$Specific\ CO_2 = \frac{CO_2\ emissions}{products\ \ produced} \tag{5}$$

where specific CO_2 is measured in t CO_2/t product.

Many organisations have developed national level energy efficiency indicators (WEC, 2008; APEC, 2001) and energy indicators for sustainable development (IAEA, 2005) to allow international comparisons. The Odyssee project has defined energy efficiency indicators for the EU countries (ADEME, 2007). Often, economic indicators, also called energy intensities, such as energy consumption per GDP, are used. A detailed description of different energy efficiency indicators has been presented by, among others, Patterson (1996) and VTT (2007).

There are many indicators or methodologies that can be used to evaluate CO_2 emissions, other environmental impacts and sustainability. Like energy intensity, emissions per GDP can be called emission intensity. For example, China measures its CO_2 emission trend based on emission intensity: when the economy is growing fast, the emissions per GDP decline. Antikainen (2010) lists the following methodologies than can be used to evaluate ecological sustainability: life cycle assessment (LCA), ecological footprint, carbon footprint, water footprint, material and mass balances, LCA based on input-output analysis, exergy analysis and other thermodynamic methods. Lovins (2004) presented a methodology to analyse the energy efficiency of the fuel cycle, i.e. along the chain of energy conversions. Lovins (2004) stated that the downstream savings, nearest the customer, are the most important because the saving in energy end-use reduces energy consumption and environmental impacts at all stages before the end-use stage.

3.4 Previous studies related to energy efficiency and CO_2 emissions in industry

The oil crisis in the 1970s increased the interest to find energy efficient solutions and energy savings. Since then, the tightening climate policy has increased this interest even more.

IPCC lists the following sector-wide energy efficiency measures for the industrial sector: benchmarking; energy management systems; efficient motor systems, boilers, furnaces, lighting and heating, ventilating and air conditioning (HVAC) and process integration (Bernstein et al., 2007). In addition, there are numerous industry-specific energy conserving technologies such as dry quenching of coke in the iron and steel industry and the shoe press in the pulp and paper industry.

At the European Union level, the energy efficiency measures are widely covered in the Reference Document on Best Available Techniques for Energy Efficiency, also called the BREF-document of energy efficiency (EC, 2009c). Based on the BREF-document of energy efficiency the Finnish energy efficiency BAT reference document was drawn up (Heikkilä et al., 2008).

Opportunities to improve energy efficiency and reduce CO_2 emissions have been studied widely both in the pulp and paper industry and the iron and steel industry. Energy efficient pulp and paper making is studied in countries with significant pulp and paper production, such as Finland, Sweden, Canada and the USA. The research of the steel industry is more diverse.

In Finland, Tekes, the Finnish Funding Agency for Technology and Innovation, has financed many technology/research programmes related to the pulp and paper industry since the 1980s. These include Raina (1988-1992), Kuitu (1988-1992), Sustainable Paper (1993-1998) and Process Integration Technology Programme (2000-2004). Climate issues have been studied in the ClimTech (1999-2002) and ClimBus (2004-2008) programmes. Biorefining technologies are studied and developed in the BioRefine technology programme of Tekes (2007-2012) and the Future Biorefinery research programme of Forestcluster Ltd[3]. At the turn of the millennium the Finnish Paper Engineers Association and TAPPI published the Papermaking Science and Technology Series. The recently updated issue 6 (Part 2) considers energy issues (Tikka, 2008), updated issue 19 environmental issues (Dahl, 2008) and updated issue 9 energy management in drying (Ahtila et al., 2010). Among others, the Technical Research Centre of Finland (VTT) and Aalto University School of Science and Technology have conducted numerous studies concerning energy efficiency and CO_2 emissions in pulp and paper production. Process integration[4] has been one of the main topics of energy efficiency research (Laukkanen, 2003; Tuomaala 2007).

Tekes has also had research programmes related to the iron and steel industry, such as Sula2 (1993-1998), where energy-efficient production of base metals was studied. Fimecc, Finnish Metals and Engineering Competence Cluster, has a programme called LIGHT (Light and Efficient Solutions) that finds solutions to reduce the energy consumption and CO_2 emissions of metal products by minimising their weight. Also, the Academy of Finland has a programme called SusEn (Sustainable energy, 2008-2011) under which the project GREENSTEEL studies the hidden potential for gross reduction in energy demand and emissions in steelmaking.

In Sweden, the optimisation of industrial energy systems and the development of process integration tools, such as advanced pinch analysis and mixed-integer linear programming (MILP), have been the focus areas of energy research in industry. Chalmers University of Technology, the Royal Institute of Technology, Linköping University and Mälardalen University have studied energy efficiency and CO_2

[3] Forestcluster Ltd is the forest sector's strategic centre in Finland.
[4] Process integration can be defined as a collection of strategies, methods and tools that focus on the efficient use of resources (energy, raw materials, water, and capital) on a systems level.

emissions in the pulp and paper production for years (Axelsson, 1998; Bengtsson et al., 2002; Heidari Tari & Söderström, 2002, Möllersten et al., 2003, Axelsson & Berntsson, 2008, Zhang et al., 2009).

In Canada, the Pulp and Paper Research Institute of Canada (Paprican) and Canmet are the central organisations doing energy research in industry. Under the Canadian Industry Program for Energy Conservation (CIPEC), Paprican studied the energy cost reduction aspect of energy efficiency in the pulp and paper industry (Francis et al., 2002). The CanmetENERGY Industrial Process Optimization group collaborates with manufacturing sub-sectors such as pulp & paper and iron & steel (Canmet, 2010). In the USA, the Lawrence Berkeley National Laboratory has studied the energy efficiency improvement and CO_2 emission reduction opportunities of various industrial sectors, including the paper and pulp industry (Martin et al., 2000) and the iron and steel industry (Worrell et al., 2001).

Energy consumption and CO_2 emissions in the steel industry have been studied at the national level in many countries, such as Japan (Gielen & Moriguchi, 2002), China (Price et al., 2002), Canada (NRCAN/CSPA, 2007), Mexico (Ozawa et al., 2002) and Sweden (Sandberg et al., 2001). Also mill- and process-specific analyses (Petela et al., 2002; Worrell et al., 2008) have been made.

International benchmarking studies on energy efficiency performance and CO_2 emissions have been made for manufacturing industries (Farla et al., 1997; Eichhammer and Mannsbart, 1997; Lehtilä et al., 1997; Karbuz, 1998; Farla and Blok, 2001; Phylipsen et al., 2002; IEA, 2007c; JISF, 2007). The World Steel Association (worldsteel) benchmarks the improvements in energy use and material efficiency of its member companies (worldsteel, 2008). Benchmarking studies are typically based on a comparison with the best performance data, i.e. best practices. The most recent world best practice energy intensity values for selected industrial sectors have been collected by Worrell et al. (2008).

National energy efficiency benchmarking for industries has been applied in the Netherlands and Belgium. In 1999, the Dutch government concluded an Energy Efficiency Benchmarking Covenant with the energy-intensive industry (IEA, 2009c). Also in Belgium, in the Flanders region, a benchmarking covenant was made with large energy-intensive industrial companies (IEA, 2006). Under both covenants, companies undertake to be among the top world performers in terms of energy efficiency by 2012. In the Netherlands and Belgium the benchmarking approach has also been applied to allocate emission allowances under the EU ETS. The possibility of using an EU-wide benchmark-based allocation methodology for the industrial sectors under international competition, such as the iron and steel industry, from 2013 onwards has been studied (Neelis et al., 2008).

At the international and national level the potentials for improving energy efficiency and reducing CO_2 emissions are typically evaluated on the basis of scenario studies. For example, the International Energy Agency (IEA) is using this methodology in the World Energy Outlook (WEO) reports (IEA, 2007a; IEA, 2009a). Also the Intergovernmental

Panel on Climate Change (IPCC) has developed emission scenarios to analyse the costs and benefits of different approaches to mitigating climate change (IPCC, 2007). Energy efficiency plays a key role in CO_2 emission reduction across both IEA and IPCC scenarios.

The Finnish Ministry of Employment and the Economy (MEE, 2008) has created the Long-Term Climate and Energy Strategy, which aims to meet the EU’s 20-20-20 targets. The Finnish Prime Minister’s Office (2009), Finnish Energy Industries (2009b) and VTT (2009) have presented their scenarios and visions to reduce Finland’s greenhouse gas emissions by 2050. The report by the Finnish Energy Efficiency Committee (2009) lists 20 measures to save energy and improve energy efficiency in industrial and service sectors, including, among others, the improvement of economic support mechanisms and providing information on the energy efficiency of products. Also, non-governmental organisations (NGOs), such as Greenpeace (2008) and Friends of the Earth (Heaps et al., 2010), have presented their own scenarios. Energy efficiency is high on the agenda in all of those scenarios. However, the emission reductions achieved by energy efficiency improvements of different scenarios are difficult to compare, because the background information presented in the reports is restricted.

The costs of emission reduction options, such as energy efficiency improvement, have been analysed in many studies. McKinsey (Enkvist et al., 2007; McKinsey, 2009) has presented the widely referenced global greenhouse gas abatement cost curves beyond business-as-usual 2030, which revealed several opportunities to improve energy efficiency with negative abatement cost, such as motor systems efficiency and insulation retrofit. Also, the IEA found end-use efficiency having negative marginal emission reduction costs when CO_2 emissions reductions relative to the baseline for the global energy system in 2050 were evaluated (IEA, 2008c). Similarly, in Stern Review (Stern, 2006) an illustrative marginal abatement cost curve and aggregate carbon abatement cost curve for the UK show negative marginal abatement costs for energy efficiency. Villa (2007) found that also in the Finnish forest industry it is possible to achieve carbon emission reductions based on energy saving investments with negative costs (the payback time of energy saving investment is less than one year). Although marginal abatement cost curves are powerful for analysing emission reduction options, there exist a number of methodological problems, such as the abatement costs are not always clear and there is no unique baseline reference technology (IEA, 2008c).

3.5 Challenges related to measuring energy efficiency and CO_2 emissions

Regardless of multiple energy efficiency indicators, the evaluation of energy efficiency improvement and related CO_2 reduction potential is not so straightforward. In many studies, the principles upon which the energy consumption and CO_2 emissions have been calculated are not presented unambiguously.

It has been found that there are many issues causing problems when energy efficiency and its development are measured. Karbuz (1998) and Farla and Blok (2001) emphasise the selection of appropriate data when energy efficiency indicators are used as a basis for policymaking or international comparisons. Among others, the following potential problems were identified: the definition of system boundaries, the calorific values used, the non-energetic use of fuels, the fuel classification and utilisation of unconventional fuels, as well as the quality of data collection. The following challenges listed by Ahtila et al. (2010) are discussed in greater detail below: variables affecting energy efficiency, the allocation problem, system boundary definitions and energy valuation.

Various factors other than the development of energy efficiency affect changes in the energy consumption of industrial processes (Eichhammer and Mannsbart, 1997). In addition to process specification, the SEC and specific CO_2 emissions of an industrial plant depend on process performance parameters such as the production rate, operation time and product quality. In addition, the utilisation of recycled materials is a major factor affecting the product mix and energy consumption of the industrial sector. Therefore, differences in indicators between countries may reflect the difference in product mix, i.e. the structure of an industrial sector (IAEA, 2005; Farla et al., 1997; Farla and Blok, 2001; Phylipsen et al., 2002; Möllersten et al., 2003). For example, Finland is a net exporter of energy-intensive products, such as paper and steel (CEPI, 2007 and worldsteel, 2009) and also a net exporter of emissions (i.e. production of exported products causes more emissions in Finland than production of imported products abroad), which makes Finland an exception among the EU countries (Heaps et al., 2010). Outside the EU there are other countries similar to Finland losing the benefit of recycling, such as the pulp and paper sector in Canada. It is noteworthy that Canada does not face the same emission reduction targets as Finland has to meet under the EU ETS, which may have effects on the competitiveness of the industrial products in the international markets.

In order to allocate the benefit of CHP production, i.e. fuel conservation between heat and electricity, many different methods have been developed. First, different allocation methods were used to price the heat and electricity produced. Recently, the allocation of CO_2 emissions in CHP power production has also become an important issue. The cost allocation is needed when different products of a CHP plant are sold to the market. The allocation of CO_2 emissions to electricity and heat is not needed under the EU ETS, since the CO_2 emissions are monitored on the basis of realised fuel consumption at the plant level. However, nowadays an increasing number of consumers are interested in the environmental impacts and carbon footprint of products. In order to calculate the specific CO_2 emissions of different industrial products, the CO_2 emissions of the electricity and heat consumed have to be determined and allocated to different products. Analogically, in LCA and environmental/carbon footprint analysis raw materials, energy consumption, CO_2 emissions and other environmental burdens have to be allocated to different products. González et al. (2003) stated that the allocation of environmental loads in processes with several useful products (co-products) is one of the most important and frequent methodological problems to be tackled when carrying out the life cycle inventory.

The recyclability of products is not usually considered when the SEC and CO_2 emissions of industrial production are monitored. Therefore, one aspect of the allocation problem is the allocation of the benefits of material recycling between primary and secondary production. Ekvall and Tillman (1997) have analysed different allocation procedures that can be considered in open-loop recycling, i.e. in a recycling process that produces material or energy for use in more than one product.

The importance of clearly defining the system boundary has been noted in some studies, such as Larsson et al. (2004), IEA (2007c) and Tanaka (2008). The study made by Tanaka (2008) showed that the specific energy consumption of crude steel production in Japan can range from 16 to 21 GJ/t, depending on the system boundaries set for the analysis and the conversion coefficient used for electricity production. One problem related to the definition of system boundaries is that the losses from self-production (or auto-production) of electricity might be included in the specific energy consumption of the industrial sector or, alternatively, in the energy sector (Farla and Blok, 2001). In the real estate sector, the wider system boundary and the thermodynamic value of energy have already been taken into account in legislation and standardisation. The standard EN 15603 (CEN, 2008) describes the methodology for calculating the integrated energy performance of buildings presents informative values for primary energy factors and CO_2 production coefficients. Such factors and coefficients are not yet available for industrial sectors.

Widening of the system boundary requires consideration of the industrial plant's connections to the outside society, such as the demand for external electricity. This creates an additional allocation problem, i.e. how the CO_2 emissions of the electricity purchased from the markets should be taken into account. The way in which the purchased electricity is assumed to be produced affects the emissions considerably (Siitonen & Ahtila, 2002; Wolf & Karlsson, 2008). Sometimes the average grid-based electricity production is used. For example, Motiva's instructions for calculating the CO_2 emissions of an individual energy consumer in Finland suggest the use of the average emission factor for grid-based electricity production if the real emission factor for purchased electricity is not obtained from the electricity supplier (Motiva, 2004). However in economics, rational decisions are based on weighting up marginal costs and benefits (Sloman, 2000). There is a common view that the marginal approach should be used for change-oriented studies, since the marginal data represent the effects of a small change in the output of products or services (Wolf and Karlsson, 2008; Ekvall et al., 2005). This approach has been used in many previous studies (Möllersten et al., 2003; Karlsson et al., 2009).

The value of energy can be measured in monetary terms or thermodynamic criteria. Nowadays renewability and environmental-friendliness, especially low CO_2 emissions, have become important valuation criteria, too. In thermodynamics, the concept of exergy enables the consideration of different qualities of different energy products. Exergy represents the ability to do work, i.e. the maximum mechanical work output that can be obtained from a certain energy input. In reality, all processes are irreversible, generating entropy and reducing the maximum mechanical work output. The exergy analysis is described in the literature (Bejan, 1996; Szargut, 2005) and widely applied to thermodynamic evaluation of thermal power plants (Ferdelji et al., 2008; Wølneberg & Ertesvåg, 2008; Siitonen & Rauhamäki, 2009). The exergy of electricity is equivalent to its energy content (equal to 1) because it can be fully converted into other forms of energy. The exergy value of primary energy is also around 1; for example the standard chemical exergy of natural gas is 1.04 times the lower heating value of fuel (Szargut, 2005). However, the thermodynamic value of heat depends on temperature and is therefore lower: for example, the exergy of district heat at a temperature of 120 °C is only 0.29 times its energy content. Energy analysis considers the value of electricity and heat to be equal, which may favour heat conservation investments.

Both fuel and electricity prices are typically determined in open energy markets. Therefore the economic value of energy is a major source of uncertainty in the evaluation of energy investments. Recently, climate policy has become an additional source of uncertainty. In response to increasing uncertainty industrial actors increase the flexibility of their operations, for example by investing in multi-fuel energy systems. Laurikka (2004) stated that the value of flexibility in energy investments grows as the uncertainty caused by climate policy increases. Based on Ashby's Law of Requisite Variety (Ashby, 1958), strategic flexibility increases the company's capability to generate the variety of responses required to maintain stability in a dynamic environment (Sanchez, 1995).

4 Results and discussion

4.1 The evaluation of different challenges involved in measuring energy efficiency and the related CO_2 emission reduction

4.1.1 Variables affecting energy efficiency and CO_2 emissions in industry

The SEC and specific CO_2 emissions of an industrial plant depend on process specification and process performance parameters such as the production rate, operation time and product quality. The case study in Paper I showed that the most important variables affecting the specific energy consumption of a steel mill were the production rate of crude steel and the ratio of utilised hot metal and recycled steel. Increasing the mill's own electricity production due to more efficient use of process gases seems to decrease the SEC of the mill site. Also, sales of energy outside the mill improve energy efficiency.

Naturally, the most significant variable affecting specific CO_2 emissions is coal consumption, since the coal used at the mill is the major source of CO_2 emissions. However, the confidence interval of coal consumption in the PLS analysis was wide, which can be partly explained by the variation in coal quality. In addition, the PLS analysis does not take cross-effects between different variables into account. So, in reality the variation in recycled steel consumption, purchased coke and crude steel production might have a greater influence on the specific CO_2 emissions. The increasing utilisation of recycled steel and crude steel production decrease the specific CO_2 emissions.

The influences of material recycling on energy efficiency were analysed in greater detail in Paper II also from the pulp and paper industry point of view. The analyses show clearly that the use of recycled material as a substitute for primary raw materials reduces average specific energy consumption both in the iron and steel industry and in the pulp and paper industry. The recyclability of industrial products differs from sector to sector. Usually, the recycling affects the raw material quality. Such is the case in paper recycling, where the fibre quality is reduced and the fibre becomes shorter. These products can be recycled a limited number of times. However, for some products, such as steel, the quality of the material remains almost unaffected.

Paper II also showed that the utilisation rate of recovered materials of industrial products should be taken into account when the specific energy consumptions of industrial sectors are compared internationally. However, it has to be noted that there might be other differences in the production mix, such as the quality of the end-products, between different countries.

4.1.2 Allocation problem

In Paper II it was shown that the use of recycled materials improves energy efficiency. Often, the products that utilise recycled materials get the whole benefit from recycling. For example, the EU ETS gives the whole benefit to the plant using recycled materials and thus having lower emissions. Therefore, emissions trading promotes the use of recycled materials but gives no incentive to develop or produce recyclable products.

From the Finnish point of view, it should be noted that large exports of highly energy-intensive products weaken the availability of recycled materials for domestic markets. Therefore, the structural change towards secondary production is not easy and some part of the energy and CO_2 emission benefits of exported recyclable materials should be allocated to primary production. Paper II presents one way to allocate the benefits of material recycling between primary and secondary production. Allocation in cascade gives lower specific energy consumption and CO_2 emissions to primary production, which would give an incentive to produce recyclable materials. However, recovered materials should have some advantages over virgin raw materials – such as lower price, greater ease of use, higher quality or some other beneficial properties - to provide an incentive for their use.

Paper III discusses the allocation of fuel consumption and costs between heat and electricity in CHP plants. There is no consistent way to valuate the process steam in industry, and no single useful method for allocating fuel costs to heat and power. Instead, the most suitable method may vary, depending on 1) the system boundary selected, i.e. the decision-making perspective 2) the type of CHP plant and 3) energy prices. Based on the results of this paper, the exergy method fits well with the combined cycle gas turbine (CCGT) plant with a condensing unit and constant fuel input. On the other hand, it is reasonable to conclude that the market-based method is the most appropriate way to valuate the heat price when heat conservation reduces the production of CHP electricity.

Both the energy method and the benefit distribution method typically used in Finnish industry overestimate the profitability of heat conservation investments from the mill perspective. The differences between the allocation methods should be understood and the most suitable method for each case should be selected on the basis of an analytical review of different allocation methods.

4.1.3 Definition of the system boundary

The analyses made in Paper I show that many common problems identified in energy efficiency studies of the steel industry can be avoided by a clear definition of the system boundaries. At the same time it is easier to see the difference between the final energy consumption and primary energy consumption of an industrial plant with its own energy production.

Figure 1 shows the different system boundaries considered in this study: A) process; B) mill and C) mill site.

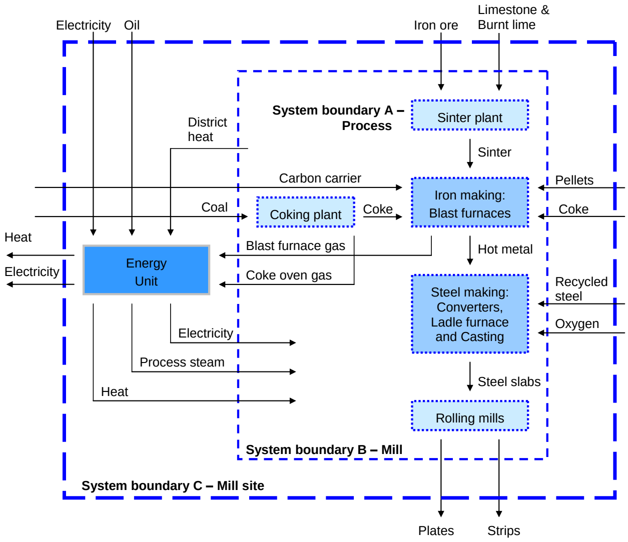

Figure 1. System boundaries of a steel mill

Paper I pointed out that depending on the perspective, different system boundaries are needed for energy efficiency and emission reduction studies. From the benchmarking point of view, it is essential that the system boundaries of compared systems, such as industrial plants, are defined in a similar way. Each steel mill has its individual configuration and in particular, there are differences in the process integration of the mills. Typically, the more integrated the mill, the more self-sufficient it is in intermediate products and energy. However, regardless of efficient utilisation of process gases, the energy consumption and CO_2 emissions of an integrated mill might be higher than in a mill using more intermediate products.

Under the EU ETS allowances are allocated at the plant level, so the definition of the system boundary should be clear. However, the self-production of energy, especially CHP production, raises the question of whether it should be part of the electricity sector or the heat-consuming industrial sector (IEA, 2008d). Another challenge is how the integration rate of the mill can be taken into account in the allocation of emission allowances. The increased process integration typically improves energy efficiency at the mill site, but may increase CO_2 emissions. For example, energy sales seem to improve the energy efficiency, but increase CO_2 emissions at the site. Also own coke or sinter production increases CO_2 emissions at the mill site and consequently the mill's need for emission allowances.

Although reducing the integration rate of an industrial plant might seem an attractive option for cutting CO_2 emissions at the mill site, the global effects of lowering the integration rate might be negative. Therefore, the integration rate of an industrial plant should be taken into account in policymaking by widening the system boundary. For example, if a benchmark-based allocation methodology is applied in the future to allocate emission allowances to the energy-intensive industries for free, the clear definition of system boundary and the inclusion of the climate effects of intermediate products used in the production process are crucial questions. Because the emission allowances have economic value, the accuracy and fairness of the allocation methodology have significant effects on the competitiveness of those industries. For reaching the global reduction of CO_2 emissions, the energy efficiency of industrial plants should be the central criterion also in CO_2 emission benchmarking as well.

Papers IV and V discuss the effects of heat conservation on CHP production. Depending on the design of the power plant, heat conservation can affect fuel consumption, electricity production or/and district heat production. If a reduction of the heat load lowers electricity production, this reduction may have to be compensated for at the national level. When there are implications outside the mill site, a wider system boundary than the mill site has to be used when energy conservation or CO_2 emission reduction is analysed.

In Paper III different system boundaries are used to describe different decision-making perspectives. The effects of a heat conservation investment as well as the profitability of the investment seem different from the mill, power plant and mill site perspectives. In addition, Paper III states that widening of the system boundary helps to avoid the fuel allocation problem.

4.1.4 The valuation of energy

Paper III discusses both the thermodynamic value and monetary value of energy. Depending on the power production type, either thermodynamic value (exergy method) or monetary value (market-base method) is suitable to evaluate the profitability of a heat conservation investment.

Paper V studies what kind of effects operational flexibility and changes in energy prices have on the realisation of the energy conservation and CO_2 reduction potential of an energy efficiency investment. The paper shows that energy prices affect the selection of operational option when there is flexibility in the process. Producing additional electricity has been the most feasible option during periods of high electricity prices. When the EUA and electricity prices collapsed in 2007, the sale of biomass was the most feasible option. Overall, after introducing the EU ETS at the beginning of 2005, the variation of cost saving in the different operational options has been larger than in the previous years. The results showed that high EUA prices give an incentive to reduce CO_2 emissions at the mill site and to achieve the CO_2 reduction potential identified in the investment phase.

4.2 The realisation of the energy conservation and CO_2 emission reduction potential in energy-intensive industries

4.2.1 Effects of system boundary selection

Paper IV shows that a heat conservation investment in a single industrial process may have different implications for primary energy consumption and CO_2 emissions at the mill site and national levels. Therefore, the national-level potential for energy conservation or emission reduction cannot be estimated by summing up mill-site effects, but also the connections to the outside society have to be taken into account. In the case of internationally integrated energy systems, such as the Nordic electricity market, there might be some transboundary effects, too.

4.2.2 Effects of operational flexibility and changes in energy prices

The case study in paper V shows that increased operational flexibility increases the cost savings of an energy conservation investment but may weaken the realisation of the energy conservation and CO_2 reduction potential. In the case of high operational flexibility in the system, the operator of an industrial power plant has greater ability to optimise in a number of different ways and consequently it is more difficult to estimate the CO_2 reduction. Therefore, increased operational flexibility may lead to less than optimum CO_2 reduction when the optimisation is made in the economic dimension – in our case study only around 70% of the expected CO_2 reduction potential was realised in the flexibility cases.

Uncertainties in the energy markets, such as fluctuating energy prices, increasing dependence on imported fuels and changing climate policy, increase the interest of industrial actors in investing in the operational flexibility of energy production. From the policymaking point of view it is important to understand that increasing operational flexibility has the potential to enable improved sustainability but that the flexibility can also be used to maximise short-term profitability. Such maximisation may result in less than optimum CO_2 reduction.

4.3 Discussion

The results above indicate that the effects of the challenges involved in measuring energy efficiency have to be understood and analysed before any conclusions on the contribution of energy efficiency towards reducing CO_2 emissions can be made. These results can be exploited in understanding the complicated interdependence between energy efficiency and CO_2 emissions as well as developing monitoring systems and economic incentives to support energy efficiency improvement and CO_2 emission reduction.

The known limitation of case studies is that the results cannot be necessarily extrapolated to other systems because each industrial plant has its own configuration. However, the selected case mills here represent typical Finnish industrial plants and Finland is acknowledged as an energy efficiency country internationally (IEA, 2007d), especially for good results achieved by voluntary energy conservation agreements between the Finnish authorities and industrial companies and the high share of combined heat and power (CHP) and district heating and cooling (DHC) production (IEA, 2008e). In Finland, CHP production has a very important role in industry, and therefore it is covered widely in this thesis. These results can be applied also to industrial plants in other countries with industrial CHP production.

This thesis includes cases from the pulp and paper industry and the iron and steel industry, but excludes some other energy-intensive industries like the chemical industry. Many of the results presented here, such as those related to the system boundary definition, could also be applied to the chemical industry. However, the utilisation of recyclable materials is not so relevant in the chemical industry: for example, many plastic products cannot be recycled.

The basis of this study has been the EU energy and climate policy and legislation. However many other countries have their own energy efficiency and emission reduction targets and, for example, in Japan a national emissions trading system is under development. So, the differences in policy framework should be remembered when these results are evaluated. Another aspect, mentioned in paper IV, is that the emission factor for grid-based electricity has a big influence on the evaluation of emission reduction at the national level: in the Nordic countries the difference between the effects at the mill site and national level is large, because coal-based condensing power with a high emission factor is the marginal production most of the time. In countries where no emissions trading or high carbon taxes exist, coal-fired power plants are often among the cheapest, so emissions reduction based on the marginal approach might give a lower emissions reduction than the approach based on average grid-based electricity production.

The scope of this study is limited to impacts at the national level. However, the Nordic energy system is integrated, so there might be some transboundary effects, too.

This study discusses the importance of an appropriate system boundary when implications of changes in electricity purchase for CO_2 emissions are evaluated. The same question is relevant in the case of other raw materials and intermediates, such as chemicals used in pulp and paper production or pellets, sinter and coke used in steel production. This issue is considered from the steel industry perspective in Paper I.

Paper II analyses the effects of recycling on the energy efficiency of iron and steel production and pulp and paper production. In the steel sector, the CO_2 emissions of primary production are considerably higher than those of secondary production. In the pulp and paper sector this is not necessarily the case. Unlike mills producing virgin pulp, mills using recycled fibre have no internally produced heat available. Whereas the energy production of virgin pulp mills is based on renewable biomass, mills using recycled fibre may have no other choice than the use of fossil fuels. So, although the energy efficiency of secondary production is better, the CO_2 emissions may be higher.

One source of uncertainty is the reliability of the used input data. Especially, in Paper II, where international statistics have been used, more information on the accuracy of the statistics and the reasons for statistical differences would be needed to compare the energy efficiencies of industrial sectors in different countries.

5 CONCLUSIONS

The aim of this thesis was to clarify how improvements in industrial processes contribute towards reduced CO_2 emissions. The statement, that energy efficiency improvement is the fastest and cheapest way of reducing CO_2 emissions generalises and oversimplifies the reality. There are different energy efficiency measures and some of them are not economically attractive. Secondly, it is a known fact that due to market barriers and obstacles the expected energy efficiency potential is lower than the economically feasible potential. This thesis clearly concretises the challenges of measuring energy efficiency and evaluating CO_2 reduction potential in relation to it. Based on the key findings of the study the following conclusions can be made:

- Many variables affect specific energy consumption in the steel industry. Therefore, it is difficult to know what the effects of energy efficiency on CO_2 emissions are and what the consequences of other factors, such as changes in production rates, are. The utilisation of recycled material can reduce the specific energy consumption of steel production and pulp and paper production significantly. Therefore, it is a variable that has to be taken into account when the energy efficiencies of different mills are compared.

- The selected cost allocation method used to valuate heat in CHP production significantly affects the profitability of heat conservation investments from the mill perspective. Therefore, some allocation methods, such as the energy method and the benefit distribution method, typically overestimate the feasibility of heat conservation. Due to heat conservation, i.e. reduced heat load, the production of CHP electricity at the mill site may be reduced, which increases the demand for external electricity.

- The realised CO_2 reduction of a heat conservation investment may seem totally different from the mill site and national level. Mill site analyses can either overestimate or underestimate the potential for primary energy conservation and CO_2 emission reduction from the national perspective. Therefore, an adequate system boundary should be used when the contribution of an individual energy efficiency investment towards meeting the targets for energy efficiency improvement and CO_2 emission reduction is evaluated:

    - The energy efficiency target has been set at the national level, so the connections of an energy efficiency investment to the outside society should be taken into account.

    - Climate change is a global challenge, so it should be ensured that emission reduction measures, such as energy efficiency improvement, implemented in an individual plant reduce emissions also globally.

    - The emission reduction potential of an energy efficiency improvement is not realised automatically; it has to be made economically attractive. So, it should be ensured by proper regulation and supporting systems that mill site decision-making leads to the desired results from the national perspective, too.

- To avoid the economic risks of changing policy, industrial actors increase the flexibility of their operation. Increased operational flexibility and changing market conditions, such as energy and emission allowance prices, complicate the evaluation of the emission reduction potential and often reduce the exploitation of the expected emission reduction potential.

In addition, the following conclusions, especially from the point of view of Finnish industry, can be made:

- A high export rate of industrial products lowers the possibility to utilise recycled materials. Therefore, part of the benefits of recycled material utilisation should be allocated to primary production – for example, in the allocation of emission allowances.

- The potential for energy conservation and CO_2 emission reduction in Finnish industry cannot be estimated by summing up the energy conservation measures reported in the energy analysis reports under the voluntary energy efficiency agreement scheme for the energy-intensive industry sector.

- In the case of an individual energy efficiency investment the CO_2 emissions of purchased electricity should be evaluated based on the marginal approach instead of the approach based on average grid-based electricity production.

- Both the energy method and the benefit distribution method typically used in Finnish industry to allocate fuel consumption to electricity and heat production in the CHP plant overestimate the profitability of heat conservation investments from the mill perspective. The most suitable method in each case should be selected on the basis of an analytical review.

Additional research work is needed to develop extended indicators and methodologies to monitor CO_2 emissions and energy use concurrently. At the EU level the targets to reduce emissions and increase the share of renewable energy are legally binding and therefore improvement of energy efficiency may be regarded as a secondary goal. Energy efficiency improvement and CO_2 reduction can often be achieved concurrently, but some emission reduction technologies, such as CCS, increase energy consumption. Therefore, combined energy efficiency and emission indicators should be developed. One option is to consider the change in energy use in relation to CO_2 emission reduction. In this way the energy input curve of emission abatement - similar to the emission abatement cost curve - could be developed. That kind of curve would show clearly what emission reduction measures favour emission efficiency, too. Another challenge is to develop primary energy factors and CO_2 production coefficients for industrial sectors. Energy use is typically used as input data in LCA and ecological and carbon footprint analyses. The intrinsic value of energy efficiency could be emphasised by analysing the energy footprints of industrial products.

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